Cooling of neutron stars: effects of accreted envelopes, magnetic field and crustal superfluidity

G. Chabrier[1], *A. Y. Potekhin*[2] *& D. G. Yakovlev*[2]

[1] *Ecole Normale Supérieure de Lyon, CRAL (UMR CNRS 5574), Lyon, France*
[2] *Ioffe Physico-Technical Institute, St.-Petersburg, Russia*

Abstract

We briefly review recent theoretical studies of the effects of accreted envelopes, magnetic fields and crustal superfluidity on the cooling of neutron stars. These effects are especially important for slowly cooling low-mass neutron stars, where direct Urca process of neutrino emission is forbidden. The effects are useful for interpretation of observations of several isolated middle-aged neutron stars.

1.1 Introduction

It is conventional to separate a neutron star (NS) into the isothermal interior and the outer heat-blanketing envelope. The envelope can be treated separately in the plane-parallel quasi-Newtonian approximation (Gudmundsson et al. [1]; hereafter GPE). The evolution of NSs is controlled by the relationship between the surface temperature T_s and the temperature T_b at the envelope bottom, at a density $\rho_b \lesssim 10^{10-11}$ g cm^{-3}. The temperature distribution in the blanketing envelope is determined by the equation (see, e.g., GPE)

$$\frac{dT}{dP} = \frac{3}{16}\frac{K}{g}\frac{T_s^4}{T^3}\,, \tag{1}$$

where g is the surface gravity, P is the pressure, and $K = 1/(K_r^{-1} + K_e^{-1})$ denotes the total mean opacity, including the radiative and electron contributions (K_r and K_e, respectively).

The first accurate model of a non-magnetized, pure iron blanketing envelope was developed by GPE. This model has been improved in recent years in several respects. The thermodynamic and transport properties of the plasma in the envelope have been updated; a possible presence of accreted, light-element surface layers has been taken into account [2, 3, 4, 6]; the effects of magnetic fields in the blanketing envelope have been analyzed [5, 6]. In addition, the effect of superfluidity of neutrons in inner NS crusts (at densities from neutron drip, $\sim 4 \times 10^{11}$ g cm^{-3}, to $\sim 1.5 \times 10^{14}$ g cm^{-3}) on the cooling has been considered [6, 7]. Other references can be found in [8].

Here we summarize how the physics of NS crusts affects the cooling. The effect is particularly important for low-mass stars, where the powerful direct Urca process of neutrino emission is forbidden by momentum conservation law.

Below we present theoretical cooling curves (effective surface temperatures as detected by a distant observer, T_s^∞ versus stellar age t) calculated with the physics input described in Ref. [8]. We use the same version of a moderately stiff equation of state in NS cores as in [8]. In this model the direct Urca process is open in the inner cores of NSs with gravitational mass $M > 1.358\,\mathrm{M}_\odot$. We compare theoretical results with observations of thermal radiation from isolated middle-aged NSs. The observational basis is the same as in [8].

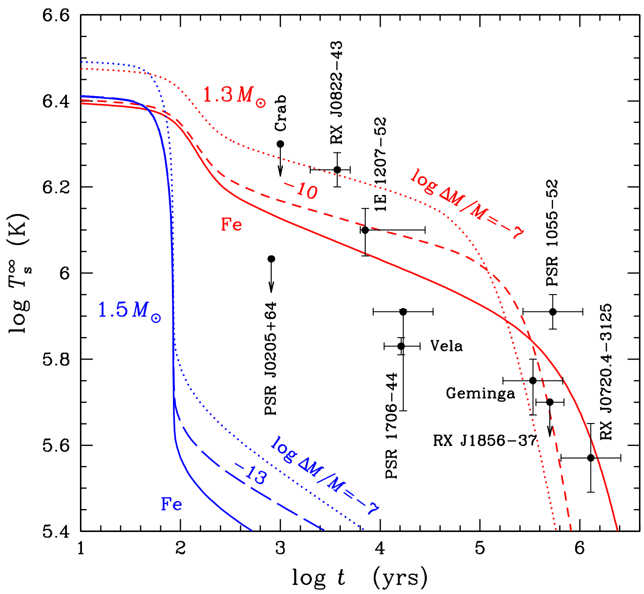

Figure 1: Cooling of nonsuperfluid 1.3 and 1.5 $\mathrm{M}_\odot$ NSs with different masses ΔM of accreted layers, as compared with observation. Solid curves refer to nonaccreted (Fe) envelopes.

1.2 Effect of accreted envelopes

Figure 1 illustrates the effect of accreted layers on cooling of nonsuperfluid NSs of two masses. A massive star with $M = 1.5\ \mathrm{M}_\odot$ gives an example of rapid cooling dominated by direct Urca process, whereas a low-mass star, $M = 1.3\ \mathrm{M}_\odot$, gives an example of slow neutrino cooling via modified Urca process. Drops of cooling curves at $t \sim 100$ yr manifest the end of thermal relaxation between stellar core and crust. Drops at $t \sim 10^5$–10^6 yr indicate the transition from the neutrino cooling stage to the photon cooling stage. Accreted envelopes have opposite effects at these two stages. At the neutrino cooling stage, the more heat-transparent blanketing envelope, due to accretion of light elements, leads to a larger surface temperature than in the case of iron envelope. In contrast, during the photon cooling stage, the lower thermal insulation of the accreted envelope leads to a faster cooling. Even a very small fraction of accreted matter ($\Delta M/M \sim 10^{-16}$) changes appreciably the cooling [2, 3, 6].

1.3 Effect of magnetic field

The thermal structure of NSs is strongly affected by magnetic fields. Landau quantization of electron orbits in a magnetic field affects the thermodynamic properties, the heat conduction, and the radiative opacities in the surface layers [10, 11, 12, 13]. In particular, Landau quantization enhances heat transport along the field lines and thus increases T_s (for a given T_b) near magnetic poles. By contrast, classical effect of electron Larmor rotation reduces electron thermal conductivity across the field lines, decreasing T_s near magnetic equator. The case of arbitrary inclination of the magnetic field to the NS surface has been studied in

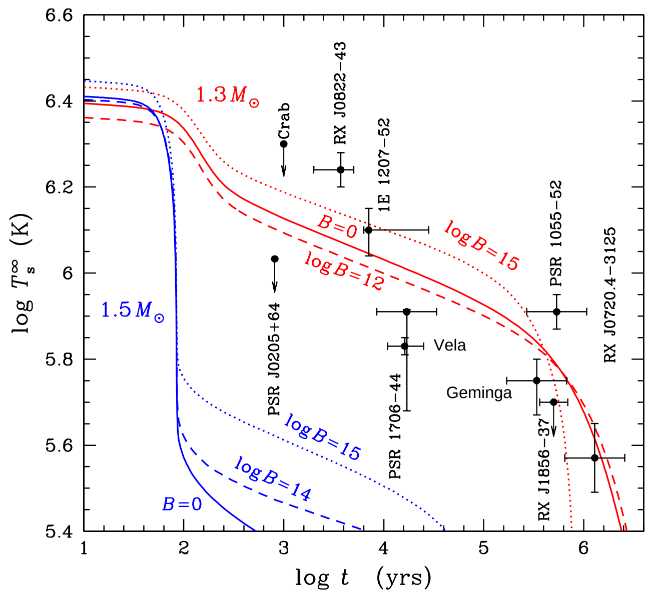

Figure 2: Same as in Figure 1 for nonaccreted envelopes with several dipole magnetic fields.

[14, 15, 16, 17]. More recently Potekhin et al. [5, 6] used improved electron conductivities of magnetized envelopes [18], as well as improved radiative opacities and equation of state of partially ionized, strongly magnetized hydrogen in NS atmospheres [12, 13], to calculate the cooling of NSs with strong dipole magnetic fields. Figure 2 displays the effect of dipole magnetic fields on the cooling of nonsuperfluid high-mass and low-mass NSs. The curves are marked by magnetic field strength at the magnetic pole. At $B \gtrsim 10^{12}$ G the temperature distribution over the stellar surface becomes strongly anisotropic, with the magnetic poles much hotter than the equator. Figure 2 shows the effective temperature T_s^∞ averaged over the surface (see, e.g., [5, 6]). As in the case of accreted envelopes, magnetic fields have opposite effects at the neutrino and photon cooling stages. Fields with $B \lesssim 10^{13}$ G make the blanketing envelope overall less heat-transparent, decreasing T_s at the neutrino cooling stage and increasing T_s at the photon cooling stage (especially for low-mass stars). Stronger fields have the opposite effect.

1.4 Effect of crustal superfluidity

Observational data can be explained assuming a weak triplet-state pairing of neutrons and a strong singlet-state pairing of protons in stellar cores (see, e.g., Ref. [8] and references therein). Let us focus on cooling of low-mass NSs in the frame of this scenario. The strong proton superfluidity switches off the modified Urca process in the cores. The cooling of these stars becomes exceptionally slow. It turns out to be rather insensitive to the equation of state and models for strong proton superfluidity in stellar cores. However, it becomes sensitive to the models for singlet-state neutron pairing in stellar crusts (whereas cooling of more massive stars does not depend on the crustal superfluidity).

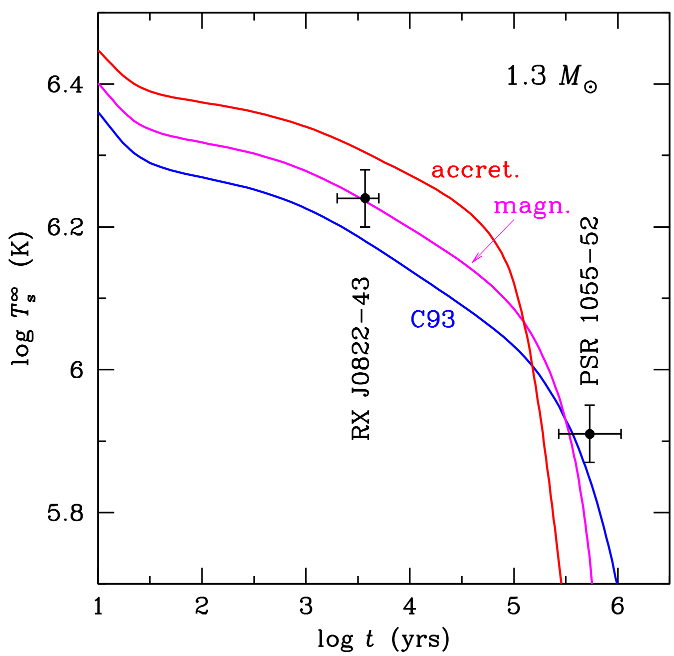

Figure 3: Cooling of NS with strongly superfluid protons in the core and superfluid neutrons in the crust (curve "C93"). Curves "accret" and "magn" include, in addition, the effects of accreted envelope ($\Delta M/M = 10^{-7}$) and surface magnetic field ($B = 10^{15}$ G), respectively.

This effect is illustrated in Fig. 3 which shows (curve "C93") cooling of a star ($M = 1.3$ M$_\odot$) with a strong superfluidity of protons (model 1p of Ref. [8]), no triplet-state superfluidity of neutrons in the core, and a model of Chen et al. [9] for singlet-state crustal neutron superfluidity. The crustal superfluidity initiates neutrino emission due to Cooper pairing of neutrons. Because the neutrino emission from the stellar core is weak, the crustal neutrino emission noticeably accelerates the cooling [6]. The acceleration is not too strong and enables to explain the observations of PSR B1055–52, although violates interpretation of the observations of RX J0822–4300. In order to explain the latter source, one can assume that it has either a strong magnetic field or an accreted envelope.

1.5 Conclusion

Our calculations show that detailed models of NS cooling, taking into account the effects of accretion, dipole magnetic fields and crustal superfluidity can help to explain observations. These effects are most important for slowly cooling low-mass NSs – isolated middle-aged NSs hottest for their ages. Although several models of crustal superfluidity are currently consistent with observational error bars of effective temperatures T_s^∞ of these objects, better measurements of T_s^∞ in the future should lead to a better determination of the surface magnetic fields and the masses of accreted envelopes of these objects and should allow one to discriminate between models of crustal superfluidity.

Acknowledgements

The work of A.P. and D.Y. is supported in part by RFBR (grants 02-02-17668 and 03-07-90200) and by the Russian Leading Scientific Schools Foundation (grant 1115.2003.2).

References

[1] E. H. Gudmundsson, C. J. Pethick, & R. I. Epstein, ApJ **272** (1983) 286 (GPE)

[2] G. Chabrier, A. Y. Potekhin, & D. G. Yakovlev, ApJ **477** (1997) L99

[3] A. Y. Potekhin, G. Chabrier, & D. G. Yakovlev, A&A **323** (1997) 415

[4] E. F. Brown, L. Bildsten, & P. Chang, ApJ **574** (2002) 920

[5] A. Y. Potekhin & D. G. Yakovlev, A&A **374** (2001) 213

[6] A. Y. Potekhin, D. G. Yakovlev, G. Chabrier, & O. Y. Gnedin, ApJ **594** (2003) 404

[7] D. G. Yakovlev, A. D. Kaminker, & O. Y. Gnedin, A&A **379** (2001) L5

[8] D. G. Yakovlev & C. J. Pethick, Ann. Rev. Astron. Astrophys. (2004) in print [astro-ph/0402143]

[9] J. M. C. Chen, J. W. Clark, R. D. Davé, & V. V. Khodel, Nucl. Phys. A **555** (1993) 59

[10] A. Y. Potekhin, G. Chabrier, & Yu. A. Shibanov, Phys. Rev. E **60** (1999) 2193

[11] D. Lai, Rev. Mod. Phys. **73** (2001) 629

[12] A. Y. Potekhin & G. Chabrier, ApJ **585** (2003) 955

[13] A. Y. Potekhin & G. Chabrier, ApJ **600** (2004) 317

[14] L. Hernquist, MNRAS **213** (1985) 313

[15] D. Page, ApJ **442** (1995) 273

[16] Yu. A. Shibanov & D. G. Yakovlev, A&A **309** (1996) 171

[17] D. G. Yakovlev, A. D. Kaminker, P. Haensel, & O. Y. Gnedin, A&A **389** (2002) L24

[18] A. Y. Potekhin, A&A **351** (1999) 787